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Thermo-optic multimode interference switches with air and silicon trenches

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ABSTRACT

A novel thermo-optic multimode interference (MMI) switch with air and silicon trenches was proposed, and the performance of the switch was simulated. In the design, one heating electrode is used to alter the refractive index at a spot image which changes the phase of this image to realize the switching function. The simulation results clearly indicate that the MMI switch can satisfy −39 dB crosstalk at two states. The electric power consumption for the MMI switch with these trenches is less than half of that of a conventional MMI switch.

1. Introduction

Most Multimode Interference (MMI), switches have been done or proposed are based on III–V semiconductor. They have relied on the electrical current injection which related to electro-optic effect to induce refractive index change in semiconductor. Therefore, electrical current injection is required for device operation, and this requirement imposes some restrictions on the device design. Since, the index change is assumed to occur at a very precise region within MMI waveguide, any excessive current spreading will seriously deteriorate in the switch performance [2,3]. The optimum position of the index modulation (IM) is potentially a very serious issue. This offset error may lead to an imbalance in the phase of adjacent self-imaging, thereby making it impossible to achieve the phase difference required for switching [4].

The optical switches based on thermo-optic effect are very attractive due to their simplicity and flexibility. The thermo-optic effect refers to the variation of the refractive index of a heated dielectric material [5]. The thin-film heater is utilized to change the refractive index and propagation characteristic of waveguide. Heat generated by the thin-film heater spread out and causes the temperature of a round region in waveguide to increase. The refractive index modulation leads to the variation of the effective MMI regions or the self-images phases within the MMI's. Consequently, the output images can be changed.

Segmented MMI's or variation of the effective MMI's has been carried out [6,7]. In which the index modulation regions are horizontally located of the light propagation. The confinement guide region is created to allow the light for passing through this region. While, the variation of the self-images phases within the MMI's by thermo-optic effect has never been used (induced index to change the phase inside the MMI region) in this type of switch, due to the natural random temperature distribution.

In this work, we propose a novel design for 2×2 thermo-optic MMI switch, where only one heat electrode is used with two trenches. The first trench is the air trench in the highest layer, and the second one is the silicon trench in the lowest layer which expands from silicon substrate to the lower cladding at the center of MMI coupler and between two self-image areas. As a result, the switching power is significantly reduced to less than half, the crosstalk is greater than −39 dB at cross or bar state, and the rise time is less than 1 ms. In Section 2, we introduce the principle and design of the MMI switch. A simulation steady-state and transient response is presented in Section 3. The FD-BPM numerical simulations are shown and discussed in Section 4.

2. Principle and design

Fig. 1 shows the schematic diagram of proposed MMI switch. As we know; the self-imaging effect is the operation principle of MMI coupler [1]. The device consists of a MMI waveguide with a width of $Wm = 30\ \mu m$ and length $L_{MMI} = 3506\ \mu m$. Light is lunched using $4\ \mu m$ wide inputs/outputs waveguides that are separated by $22\ \mu m$.

The dimensions of the MMI switch were calculated using the well known relation for general interference in MMI waveguide [1]. The length is set to $3L_\pi$ (where L_π corresponds to the beat length) such that, light coupled to the upper input waveguide will be imaged into the lower output waveguide during the cross state (off-state), as shown in Fig. 2(a).

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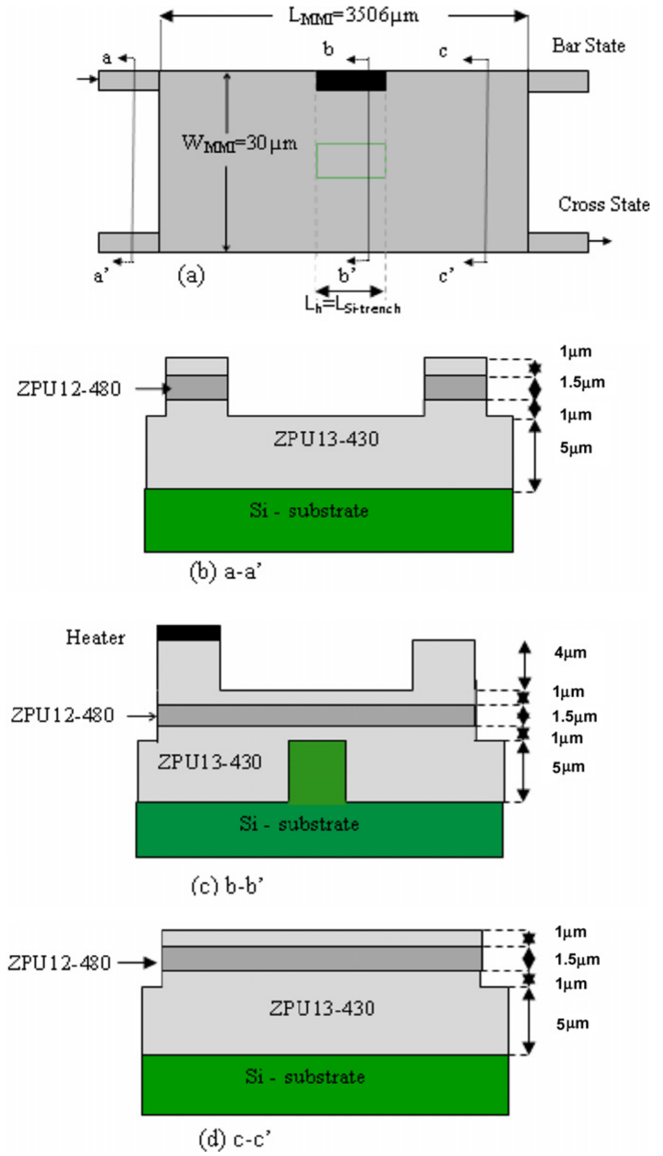

Fig. 1. (a) Schematic diagram of the MMI-based optical switch, (b) aa' cross section, (c) bb' cross section, and (d) cc' cross section.

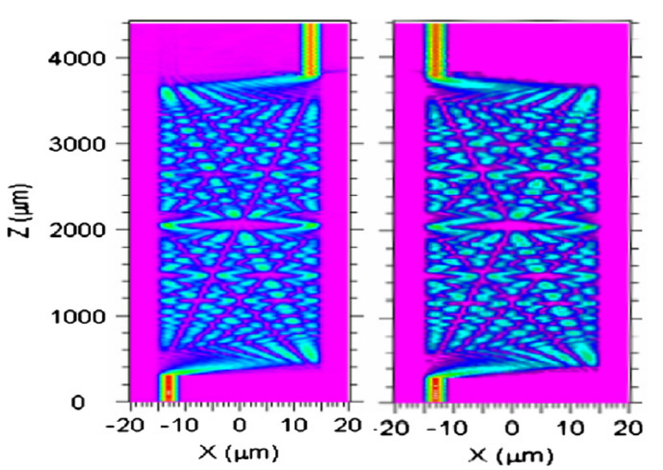

Fig. 2. Beam propagation characteristics (a) without index modulation (cross state) and (b) with π phase shift applied to index modulation region (bar state).

The proposed device is a ridge waveguide as shown in Fig. 1 with assumed materials are ZPU series from Chemoptics Co. Ltd. which consists of a core layer of ZPU12-480 with refractive index 1.48 and thickness = 1.5 μm surrounded by upper and lower cladding regions of ZPU13-430 with refractive index 1.43. The structure is a strong guiding ridge waveguide, with high lateral index contrast due to the lateral air interface and high transverse index contrast ($\Delta n = 0.05$) between the core and cladding regions.

The metal heater, has a complex refractive index with an imaginary part contributing to the attenuation of light. The metal heater, is thus an optical absorber or attenuator, and must be located a safe distance from the guiding layer to ensure low-loss phase shifting [8]. The upper cladding should be thicker than 4.6 μm [2]. For safety, a value of 5 μm has therefore been chosen to avoid the attenuation due to metal heater.

The heater layer region as shown in Fig. 1(c) at the middle of waveguide length has air trench at upper cladding layer to confine the heat from heater to guiding layer and limits the heat diffusing, more details in the next section. Furthermore, it has silicon trench which expands to the lower cladding layer at an empty region from light intensity.

The key parameter for the operation of the device is that the input light forms a pair of well defined self-images exactly at the middle of switch, and along the central axis of both access waveguides; as shown in Fig. 2. In the absence of applied power, light coupled to the first input waveguide is emitted from the second output waveguide, and vice-versa. However, when a π phase shift is applied to either one of the self-images, light coupled to the first input waveguide will be imaged onto the first output waveguide, as shown in Fig. 2. The phase shift is controlled by the parameters in Eq. (1) [3].

$$\Delta\phi = k.\Delta n.L_h \tag{1}$$

The phase shift, is induced by the change of refractive index n along the tunable section of heater length L_h for a signal with a vacuum wavelength $\lambda = 1.55$ μm, where $k = 2\pi/\lambda$. The change of refractive index is dependent on the thermal coefficient of material $\mathrm{d}n/\mathrm{d}T$ and change of temperature ΔT [5].

$$\Delta n = \frac{\mathrm{d}n}{\mathrm{d}T}.\Delta T \tag{2}$$

The thermal coefficient of ZPU12-480 is $-1.8 \times 10^{-4}\,^{\circ}\mathrm{C}^{-1}$, from Eqs. (1) and (2) the ΔT in Eq. (3) is sufficient to change phase to π.

$$\Delta T = \frac{4305 \times 10^{-6}}{L_h} \tag{3}$$

The length of self-images inside MMI region is proportional to the width of MMI. It is important to do trade off between width of MMI and length of a spot image.

3. Thermo-optic MMI switch analysis

The performances of thermo-optic MMI switch have been investigated using commercial simulation software packages. BeamPROP from Rsoft Photonic is based on Finite deference Beam Propagation Method (FD-BPM) which used for analyzing light

Table 1
Thermal parameters used in the simulation

	K (W/m C)	c_p (J/kg C)	ρ (kg/m^3)
Cr	94	450	7150
ZPU12-480	0.2	1300	1200
ZPU13-430	0.2	1300	1200
Si	163	703	2330

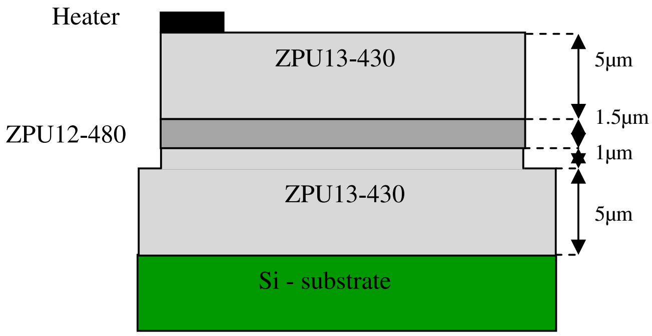

Fig. 3. Cross section of conventional MMI.

propagation at steady state. Femlab from Comsol is based on Finite Element Method (FEM) which used at dynamic state (transient state) for getting the rise time and steady state for analyzing the thermal distribution.

3.1. Thermal analysis

In order to evaluate the thermal transient and steady-state response of the device, the equation to be solved is the heat transfer Fourier's equation in transient condition with constant thermal conductivity [9,10].

$$\rho.c_p.\frac{\partial T}{\partial t} = K.\nabla^2 T + Q(x, y, z, t) \quad (4)$$

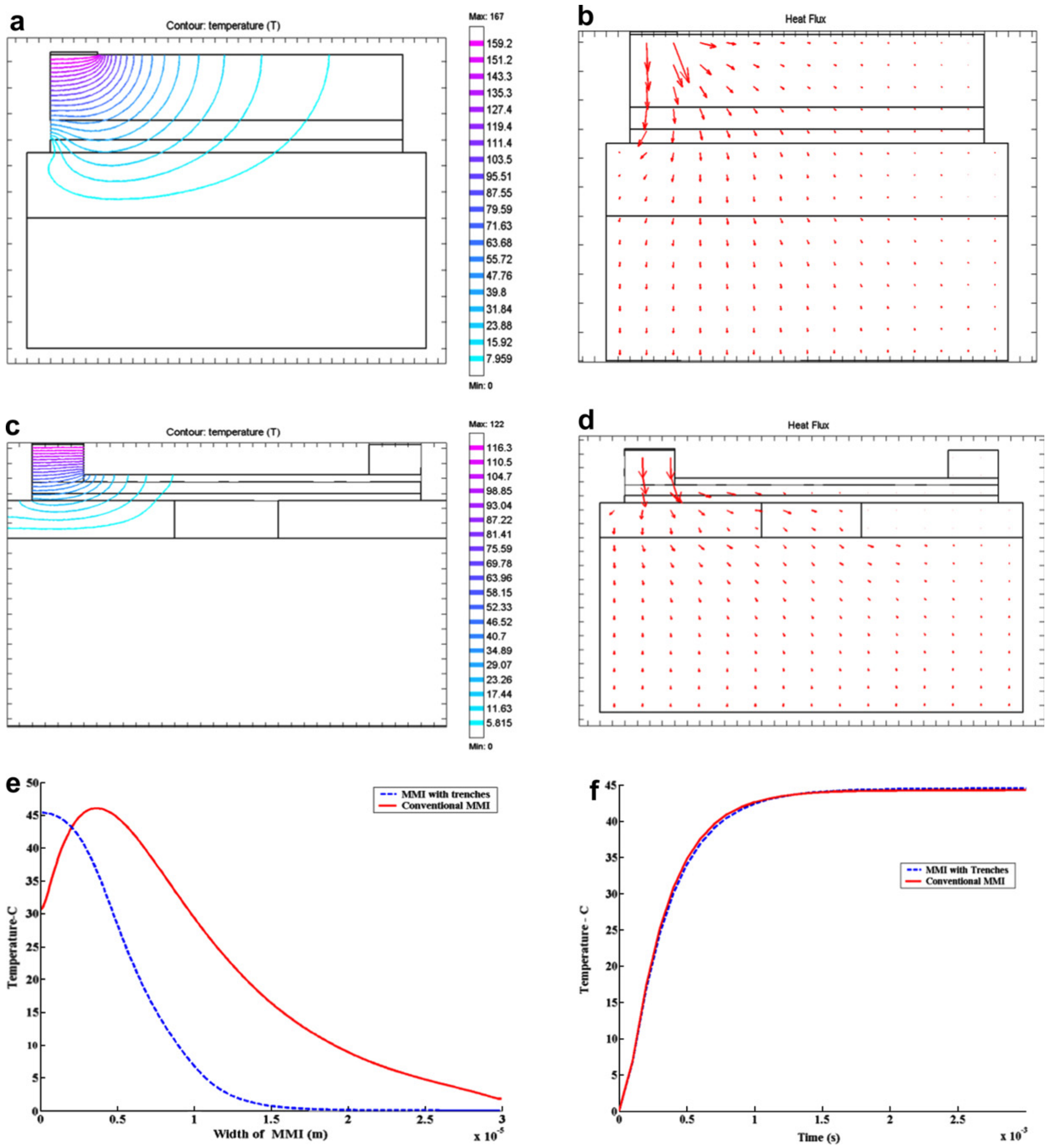

Fig. 4. Simulation results based on FEM of the temperature distribution of (a) 2D conventional MMI, (b) 2D MMI with air and Si trenches, (c) 1D at center of guiding layer for both structures, and (d) rise time of the conventional MMI and MMI with trenches.

Where ρ = Density of materials (kg m^{-3}), c_ρ = Specific heat (J kg^{-1} °C^{-1}), K = Thermal conductivity (W m^{-1} °C^{-1}), $Q(x, y, z, t)$ = Heat generation rate per unit volume (W m^{-3}).

$$T(x,y,z,t)_{t=0} = T_0 \tag{5}$$

And the boundary conditions are:

$$\frac{\partial T}{\partial s} = 0 \text{ on the top and lateral surface} \tag{6}$$

$$T = T_0\ (0^\circ C) \text{ on the bottom surface} \tag{7}$$

Eq. (5) describes the mechanism of heat transfer which is conduction, ignoring the convection heat transfer [11]. The boundary conduction in Eq. (3) states that lateral and top surfaces are adiabatic, while Eq. (4) assigns affixed temperature of the bottom and considers silicon a perfect heat sink [5]. Table 1 contains the thermal parameters used in the simulation. In order to obtain the waveguide temperature profile, Eqs. (1)–(3) are solved using the finite difference or element numerical methods [8,10].

3.2. Reducing thermal coupling

The thermal coupling coefficient representing the magnitude of temperature field interference between the two image regions in the center of MMI waveguide, is defined as

$$\eta = \Delta T_2/\Delta T_1 \tag{8}$$

where ΔT_2 and ΔT_1 are the temperature rises in the region 2 and 1, respectively.

Fig. 3 shows the cross section of the conventional MMI. The performance comparison will be done between the conventional MMI and MMI with air and Si trenches.

A detailed analysis was made to evaluate the accuracy and the operation speed of thermo-optic device. The finite element method (FEM) in Comsol software was used to perform a steady-state and transient thermal analysis of the system to evaluate temperature profile, driving power and transient response of MMI switch.

The driving power in each structure is different. It is adequate to increase the center of guiding layer temperature to 43 °C as stated in Eq. (3) at 100 μm heater length.

Fig. 4(a) and (b) shows steady-state two dimension (2D) temperature profile of two structures and Fig. 4(c) shows steady-state one dimension (1D) temperature profile in the center of guiding layer of two structures.

According to the Eq. (7), the thermal coupling efficiency of the conventional MMI and MMI with trenches are 0.089 and 0, respectively. Steady-state simulations confirmed good heat confinement in the second structure. In the next section the heat confinement effects of the MMI switch performance is revealed. The rise time for two structures is less than 1 ms as shown in Fig. 4(d).

4. Results and discussion

The optical and thermal behaviors of proposed MMI switch were verified by BeamPROP, a software based on finite difference beam propagation method (FD-BPM) [12].

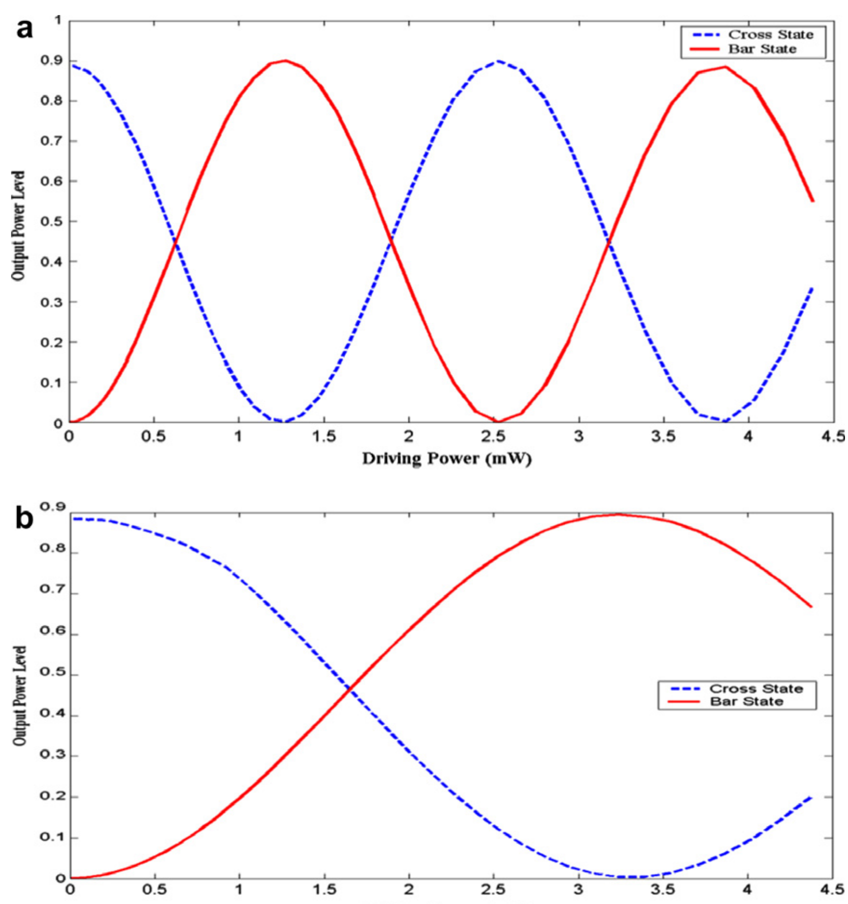

Fig. 5. Simulation results based on FD-BPM of output power level versus driving power of the MMI switch at cross state and bar state (a) MMI with trenches and (b) conventional MMI.

In this simulation, an induced refractive index change of $\Delta n = -8.1 \times 10^{-3}$ in the guiding layer is sufficient to change the phase between the self-images by π. The changing phase is done by certain value of applied power which depends on the structure as shown in Fig. 5.

The simulation result shows that the crosstalk of conventional MMI and MMI with trenches is greater than −39 dB at the cross state, while at the bar state are −23 dB and −39 dB, respectively. When the power is applied to change the state of switch, the crosstalk in the MMI with trenches is constant, while in the conventional MMI it is deteriorated, due to the defused thermal effect to the second image area. As shown in Fig. 5, the applied power for the MMI switch with trenches and conventional MMI switch are 1.35 mW and 3.4 mW, respectively.

The multimode interference waveguide with trenches will confine the heat transfer from the heater to a spot image region which maintains the crosstalk when the switch changes from one state to the other and reduces the power driving to less than half.

5. Conclusion

With the aid of the self-imaging principle of multimode interference (MMI), a novel structure of thermo-optic switch was proposed and investigated. The simulation results based on FEM and FD-BPM are presented. It shows that the switching power is less than half of conventional MMI switches. In addition, the switch shows constant crosstalk of −39 dB at the cross and bar state in comparison to the conventional MMI which will be deteriorated to the −23 dB at the bar state.

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